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THE PROSPECTS FOR ACTIVE SHIELDING

R. H. Levy

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by

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ABSTRACT

A review is given of the reasons for the interest in active shielding and the types of missions for which an active shield would be particularly desirable are discussed. Recent work on active shielding is reviewed.

Electrostatic shielding is ~~then~~ discussed. In general, the maintenance of an electrostatic field for shielding purposes will require the expenditure of power owing to the presence of a neutral highly conducting plasma. Estimates of the power required are extremely high, and electrostatic shielding appears unattractive.

Magnetic shielding is discussed ~~next~~. The virial theorem on the weights of magnetic field coils in space is explained, and it is shown how this theorem can be used to make a direct comparison between the use of a material as an element in a structure and as a stopping material for energetic protons. The result of this comparison is that for sufficiently large sizes magnetic shielding will always be superior, but that the sizes involved are extremely large. The way in which the critical size scales with the strength to weight ratio for structural materials and the magnetic field strength is discussed. This general view is supplemented by a review of the status and prospects for large superconducting radiation shields with particular emphasis on those features which are likely to make the minimum weights estimated by the virial theorem unduly optimistic.

~~In conclusion,~~ the possibility of shielding a space craft by blowing a hole in the interplanetary magnetic field (along which the protons move) with an atomic bomb is mentioned. It appears that such a shield would violate Liouville's theorem.

THE PROSPECTS FOR ACTIVE SHIELDING

R. H. Levy

I. Introduction

Shielding the astronaut against the various forms of penetrating radiation likely to be encountered on a space trip is one of many difficult problems facing the space ship designer. Perhaps it is fair to say that at this stage it is the most uncertain of all the environmental factors which must be considered in the design.

Estimates of the shielding required for the first travelers to the moon are low, but as permissible doses decline, the shielding requirement will increase. Again, we may anticipate a desire to fly extended missions in those regions near the earth (or other planets) where substantial fluxes of trapped radiation are to be found, thus imposing a severe shielding requirement on the designer. Interplanetary travel involving substantial transit times will make the occurrence of large solar flares during the trip virtually certain, and here again a sizable shielding problem is involved. Finally, for any mission, as the number of individuals undertaking it increases, permissible radiation doses will decrease, so that shielding will inevitably grow in importance as the era of space flight progresses.

It is the purpose of this note to make some general remarks on various methods of shielding which might be used other than the standard one of interposing a substantial amount of matter between the astronaut and the radiation. The importance of such methods is directly related to the

weight involved in bulk shielding. We shall in this note consider only the radiation hazard due to high energy protons since it appears at present that such protons constitute the most important natural source of danger to the astronaut.

II. Electrostatic Shielding

In order to stop a proton with an electrostatic field, the necessary potential rise in the field (in volts) must be numerically equal to the energy of the proton (in electron volts). Thus, one must at once consider potentials in the order of 10^7 to 10^9 volts.

Two methods of obtaining such potentials may be discussed. In the first, one maintains a positive charge on the space ship such that its potential relative to infinity has the required value V. This has the immediate result that electrons will bombard the ship, each having an energy equal to V electron volts. Thus, one has exchanged one form of radiation for another. Since the stopping of electrons with such energies will involve substantial production of highly penetrating bremsstrahlung, the advantage of such a method is not obvious. Furthermore, in order to maintain the potential, one would have to accelerate electrons away from the ship with this same energy V. This operation is quite difficult by itself, but, in addition, will consume a substantial amount of power.

An alternative method of generating the required potential drop would be to maintain it between, say, two concentric spherical shells. The achievement of the necessary potentials in this way is at present beyond the reach of ground based machines; and the space environment would not appear to make the problem any easier, especially since the conductors would both be essentially unshielded against galactic cosmic rays.

III. Magnetic Shielding

Magnetic shielding using superconducting field coils appears to offer an attractive shielding method provided only that the engineering problems involved in the construction of the large coils involved prove to

be tractable. It has been shown[1] that in such a shield the heaviest item by far would be the structure required to contain the magnetic stresses. In this note we shall use a theorem[2] on the minimum (ideal) weight of this structure to estimate the minimum (ideal) weight of a magnetic shield. In this way we will obtain some impression of the gains which are potentially available in a magnetic shield.

The structural weight theorem states that if it is required to confine a magnetic field containing energy E_M by using a structural material having density ρ and allowable stress σ , the mass of material required (M_s) is always greater than E_M (ρ/σ),

$$M_s \geq \frac{\rho}{\sigma} \quad E_M \tag{1}$$

The equality holds only if each element of the structure is in tension and at its allowable stress. The quantity ρ/σ is a property only of the structural material. For our purposes it is conveniently quoted in kilograms of structure per joule of stored magnetic energy, but may be more familiar when quoted as a specific strength in inches, being the length of a wire of the material that could support itself under gravity. Two examples are quoted in Table I, the one for aluminum being somewhat conservative, and the one for titanium being somewhat optimistic.

Table I

Strength of Materials

	Aluminum	Titanium (-423°F)
Stress	50,000 psi	230,000 psi
Strength to Weight	7.8×10^{-6} kg/joule $.52 \times 10^{6}$ inches	2.9×10^{-6} kg/joule 1.4×10^{6} inches

An extremely simplified view of the shielding problem is shown in Fig. 1. We consider the surface of a shielded region. Outside this surface we have a uniform magnetic field B parallel to the surface; the thickness of the magnetic field is Δ. Now it is clear at once that if proton trajectories are to be strongly affected by the magnetic field, the thickness of the

magnetic field must be of the order of the proton Larmor radius. A more detailed study shows that the "worst" proton is the one that approaches in the direction illustrated in Fig. 1. To shield against this proton it is clear that Δ must be one Larmor diameter. Thus, $\Delta = 2p/eB$ where p/e is the momentum to charge ratio of the incident proton. Now, the energy in the field per unit surface area is just $(B^2/2\mu_o) \cdot \Delta$, and with this surface distribution of energy we can (by the structural theorem) associate a structural mass per unit surface area. This mass per unit area can be regarded as a "range" in the same sense that once calculates the "range" of a proton in a solid material. Denoting it by R_B we find

$$R_B = \frac{\rho}{\sigma} \frac{B^2}{2\mu_o} \cdot \Delta = \frac{\rho}{\sigma} \frac{(2p/e)^2}{2\mu_o} \cdot \frac{1}{\Delta} \tag{2}$$

With this formula we can now compare, say, aluminum as a bulk material for stopping protons and aluminum as a structural material for supporting field coils for stopping protons. This comparison is shown in Fig. 2 for a value of ρ/σ between the two values quoted in Table I.

The first thing to note from this figure is that magnetic shielding improves as we go to larger sizes and lower fields. Of course, at some point it is no longer reasonable to neglect the contributions of the superconductor, insulation, etc. to the total mass; but the general trend of the numbers is certainly correct.

Since the results shown in Fig. 2 appear to be encouraging, it is appropriate here to list the idealizations which led to them, and which will be violated, more or less, in a real system.

1. Every element of the structure is in tension, and the cross section of each element is such that the tension is the maximum allowable.
2. The magnetic field is uniform and parallel to the surface of the shielded region.
3. The weight of the system is entirely in the structure required to support the magnetic stresses.

We will not in this note proceed to more detailed consideration of the errors involved in these assumptions; we will, however, define the

limit on how much progress can be made in the direction of reducing the weight of a magnetic shield simply by increasing its size and decreasing the field strength.

It is clear that one cannot expect to gain much beyond the point where Δ becomes of the order of the size of the shielded region. We will make this point quantitatively by resorting to a further idealization. We imagine a spherical shielded region or radius R, as illustrated in Fig. 3, surrounded by a magnetic field of thickness Δ. Now this configuration is topologically impossible since div B = 0 and a magnetically shielded region must always be multiply connected. Thus, in considering the results we will obtain from the idealization of Fig. 3, we will have to bear in mind that theré is a topological factor to be considered in estimating real weights; or, alternatively, some part of the surface must be shielded by solids. With this limitation in mind we proceed by noting that Δ must still be one Larmor diameter. The volume occupied by the magnetic field is

$$\frac{4\pi}{3} (R + \Delta)^3 - \frac{4\pi}{3} R^3 \tag{3}$$

so that the minimum structural mass is, from Eq. (1),

$$M_s = \frac{\rho}{\sigma} \frac{1}{2\mu_o} \left(\frac{2p}{e}\right)^2 \frac{4\pi}{3} \left[\frac{3R^2}{\Delta} + 3R + \Delta\right] \tag{4}$$

The last term in this expression clearly has a minimum when $\Delta = \sqrt{3}\, R$ verifying our assertion that Δ should be of the order of magnitude of the size of the shielded region. With this value of Δ, the minimum weight is

$$M_s = \frac{\rho}{\sigma} \frac{1}{2\mu_o} \left(\frac{2p}{e}\right)^2 \frac{4\pi}{3} (3 + 2\sqrt{3})\, R \tag{5}$$

and this quantity is shown in Fig. 4 for various values of the proton energy. Also shown in Fig. 4 are the corresponding weights for solid spherical shields having thicknesses appropriate to the proton energy. It is seen that here again for all reasonable sizes of the shielded volume and energies of the incident proton stream there is an advantage to be realized by shielding magnetically. However, this is, as has been pointed out, an idealized

calculation. It is not possible at present to estimate with much precision just what penalty is involved in going from the idealized situation of Fig. 4 to some real situation. However, in Fig. 5 a shield is illustrated for which the weight was calculated in Ref. 1. For 100 m^3 shielded volume and for 1 Bev protons the weight was found to be about 3×10^5 kg, and this point is marked on Fig. 4 as a "Real Magnetic Calculation." The difference between this weight and the ideal weight of 10^4 kg can be interpreted as a measure both of the prospects for magnetic shielding and of the ingenuity which has to date been exercised in the design of such shields. Further study of magnetic shields is clearly warranted and some effort should be made to pin down the real weight and operating problems involved with actual hardware. In this connection it is worth pointing out that each kg of structure in Fig. 4 corresponds to something on the order of a megajoule of stored magnetic energy. The superconducting coil with the largest energy storage known to the author to be presently functioning[3] has an energy storage of 45,000 joules, at leat three orders of magnitude smaller than anything that might be useful for radiation shielding.

IV. Explosive Shielding

One final method of shielding seems worthy of mention, although its operation is many orders more undertain than those discussed. Furthermore, the reason for discussing it is chiefly to point out that it apparently cannot be done.

The method in question is illustrated in schematic form in Fig. 6. The principle is as follows: An explosion with a yield in the megaton range takes place in an ionized medium containing a weak magnetic field. A large fraction of the energy released in the explosion is tied up in the kinetic energy of the debris of the bomb, its case, etc. All this material can be expected to be ionized, and in its expansion it will interact with the ambient magnetic field in such a way as to make a large bubble empty of both field and plasma. In this way the field lines in the interplanetary plasma will be bent around the outside of the bubble, and individual high energy protons might be expected to follow these field lines around the outside of the hole.

The difficulty with this method is not in protecting the space ship from the effects of the explosion, for the size of the bubble must be many times the radius of the earth and the bomb could easily be exploded a safe distance from the ship. In fact, it seems likely that such a bubble could be made and might persist for some minutes. However, the magnetic field produced in this way cannot exclude the high energy protons even in the extreme case where the size of the bubble is large compared to the Larmor radius of the incident protons. For it is easy to find proton paths which go through the bubble. The existence of such paths, when taken together with the form of Liouville's theorem suitable for the motion of charged particles in a magnetic field,[4] guarantees that the flux in the interior is just the same as that in the exterior. Thus, no advantage appears possible from this method.

In conclusion it may be worth pointing out that this is a fortunate circumstance. For if it were not so, one might expect the magnetosphere to act somewhat like the bubble described above, in that the interplanetary field lines to some extent go around it. Then, if there were a shielding effect, we would have to conclude that measurements of the flux of solar protons made within the magnetosphere were suspect and that the intensity of these protons in free space might be much higher than suspected. There is, at present, no evidence of such an effect, although there is not much evidence from beyond the magnetosphere.

Acknowledgment

The author wishes to thank Dr. H. Petschek for the many helpful discussions in the course of this work.

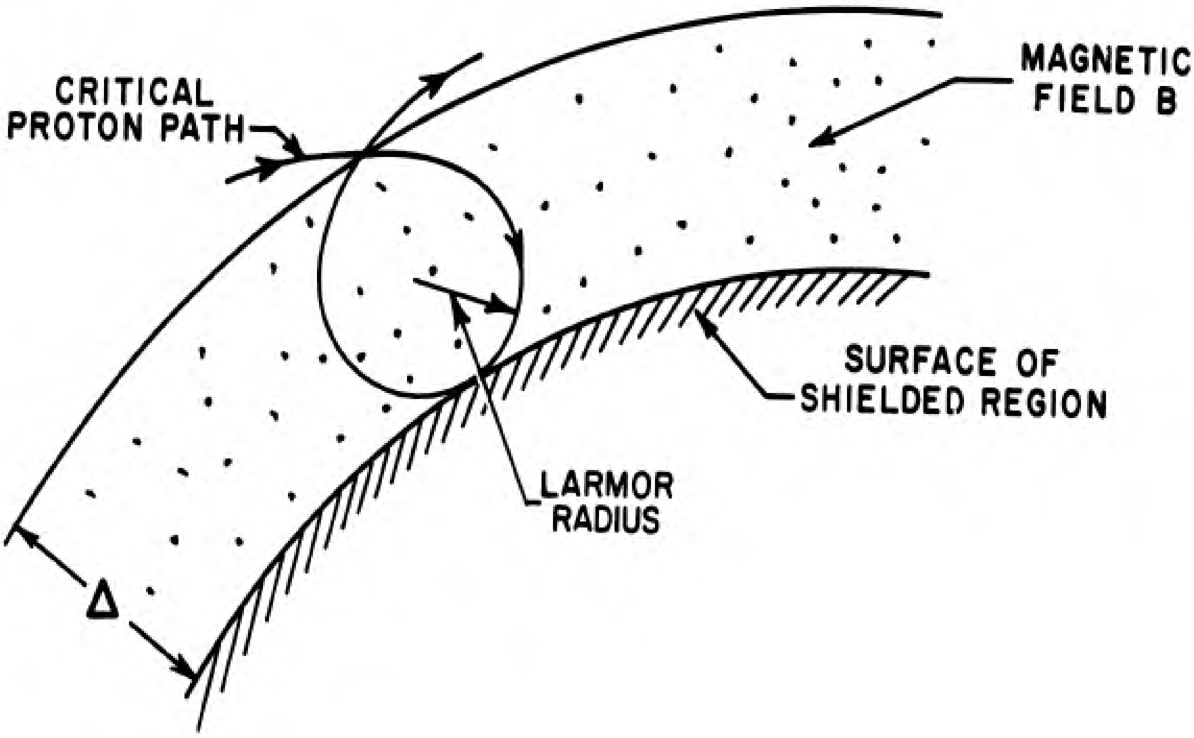

Fig. 1 This figure illustrates in a schematic manner the way in which a surface may be shielded against charged particle radiation with a magnetic field which is parallel to the surface.

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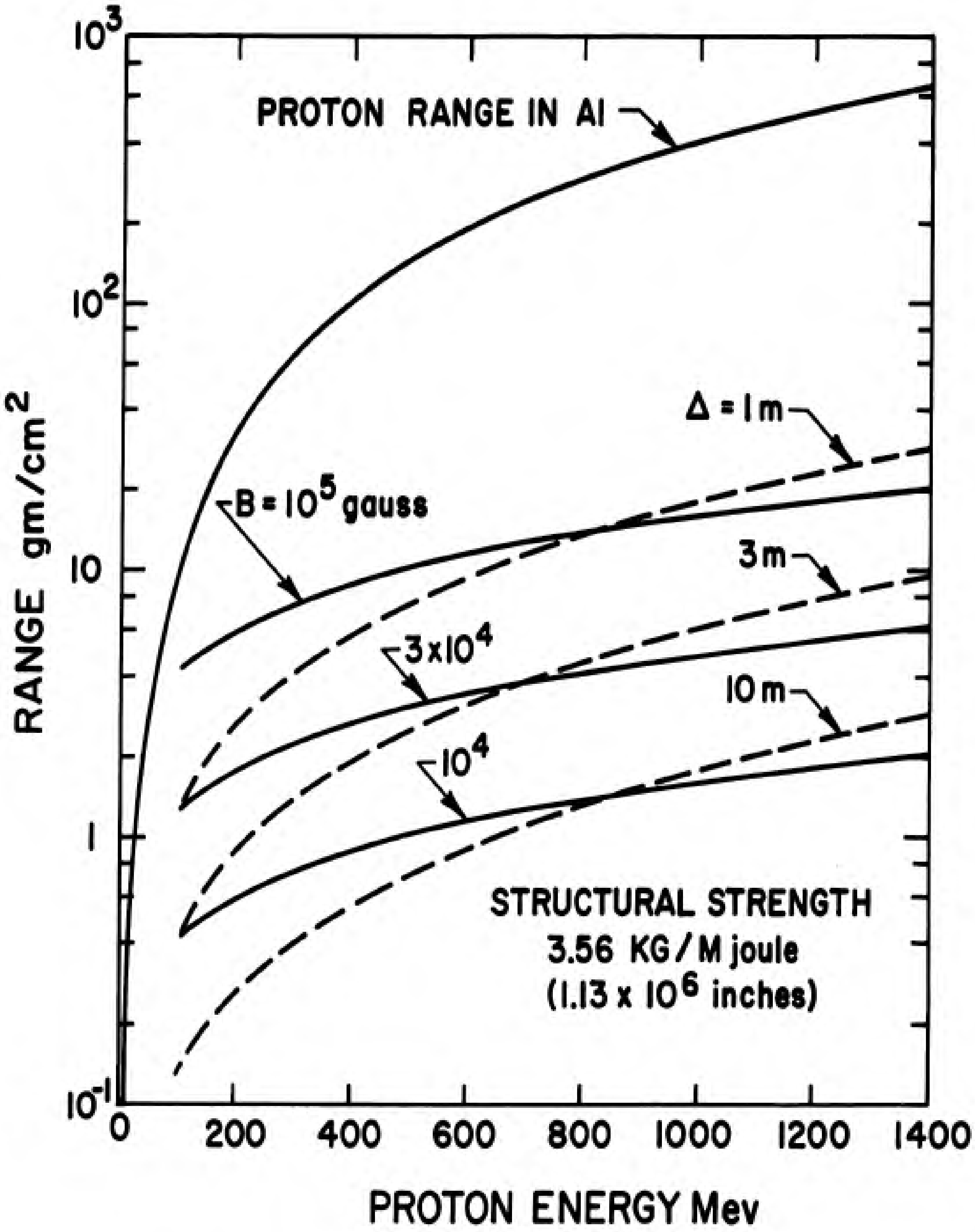

Fig. 2 This graph gives the mass per unit area (under idealizing assumptions) of a magnetic shield and compares it with the mass per unit area of a bulk shield for various field strengths and sizes.

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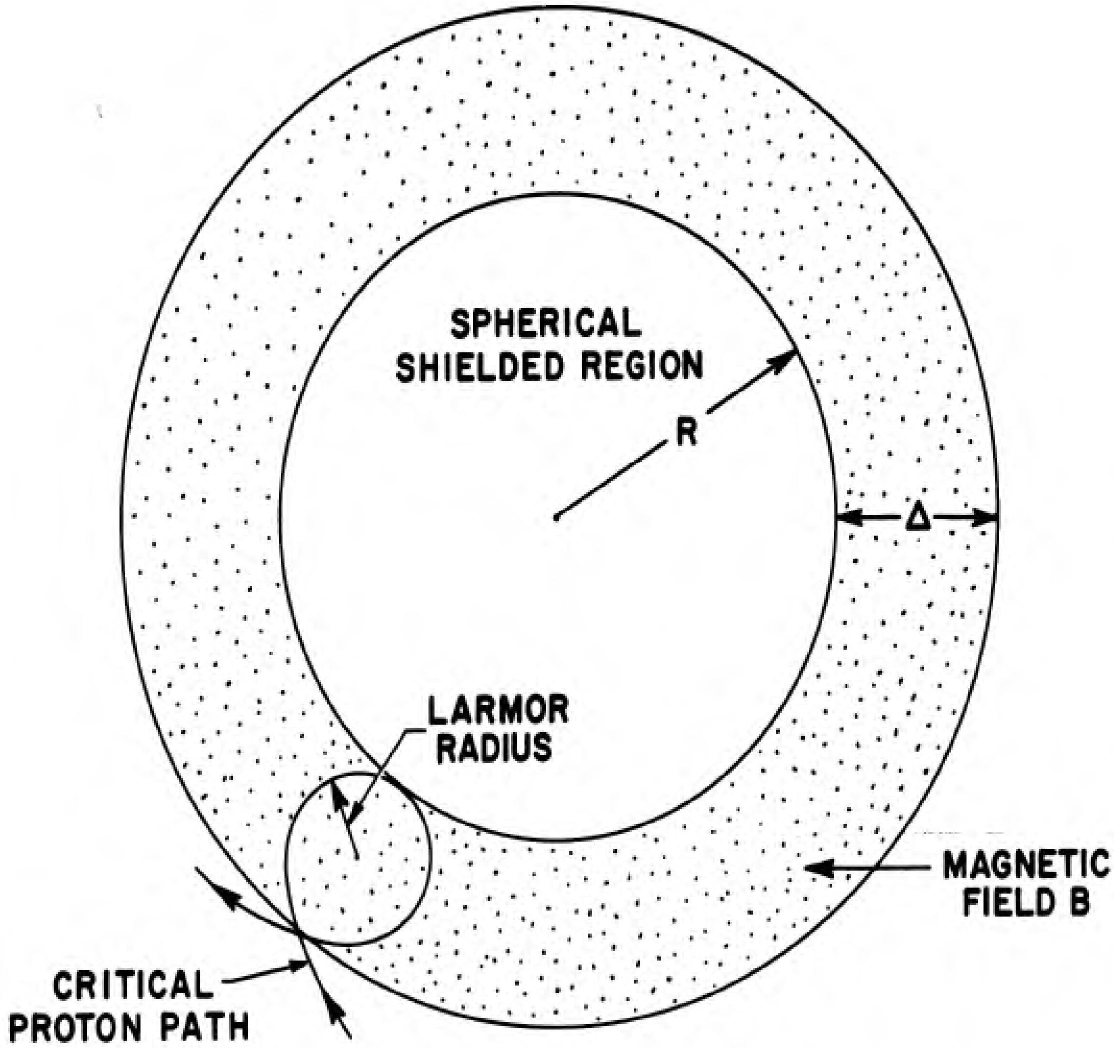

Fig. 3 This figure illustrates in a schematic manner the way in which a spherical cavity might be shielded with a magnetic field. Note that the field configuration shown is impossible; it does, however, represent a reasonable idealization of a practical configuration.

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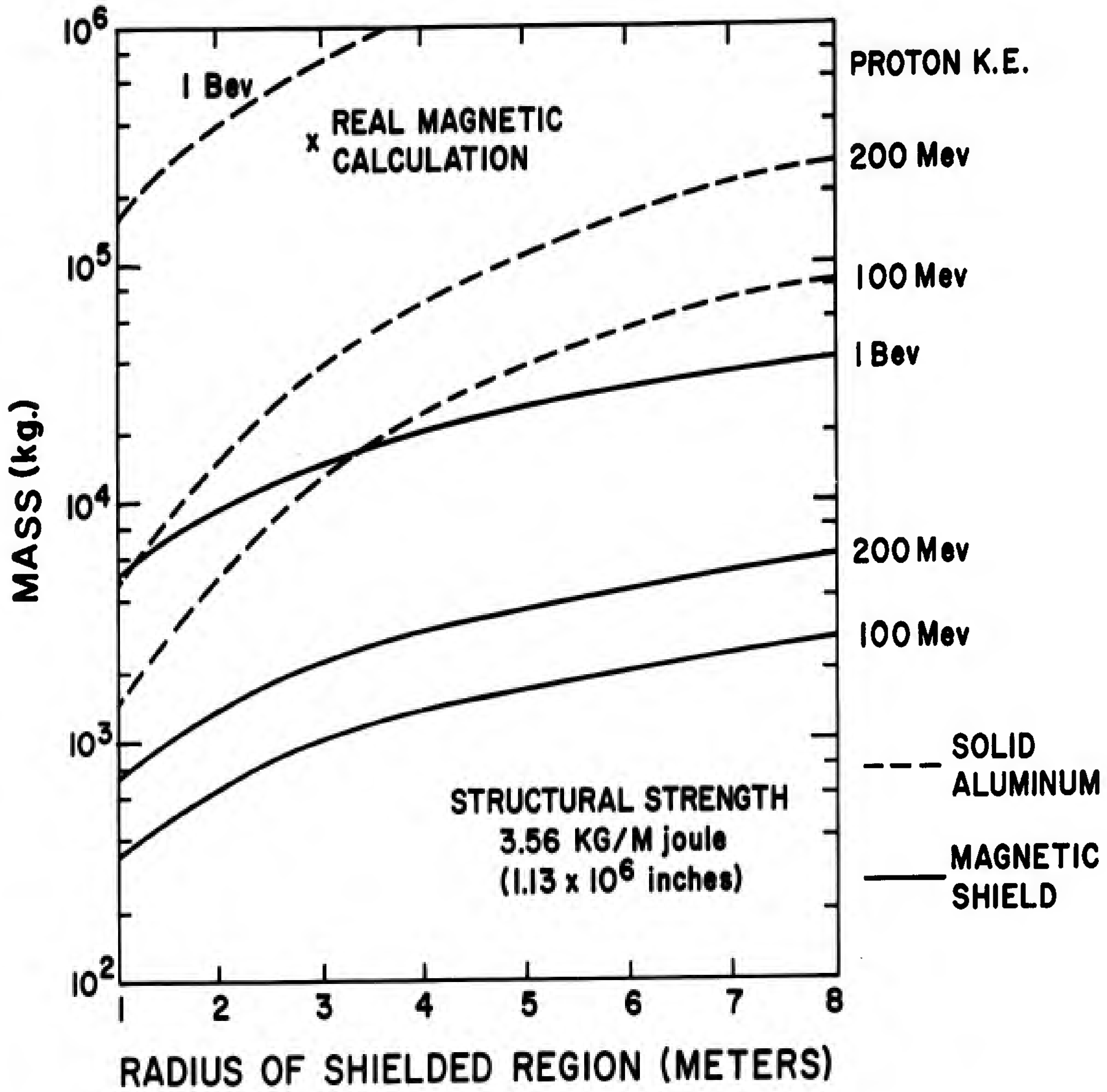

Fig. 4 This graph gives the mass (under idealizing assumptions) of the magnetic shield illustrated in Fig. 3. It also gives the mass of the bulk shield required to perform the same task, not counting secondaries, and, in addition, a more realistic calculation of a magnetic shield from Ref. 1.

9055

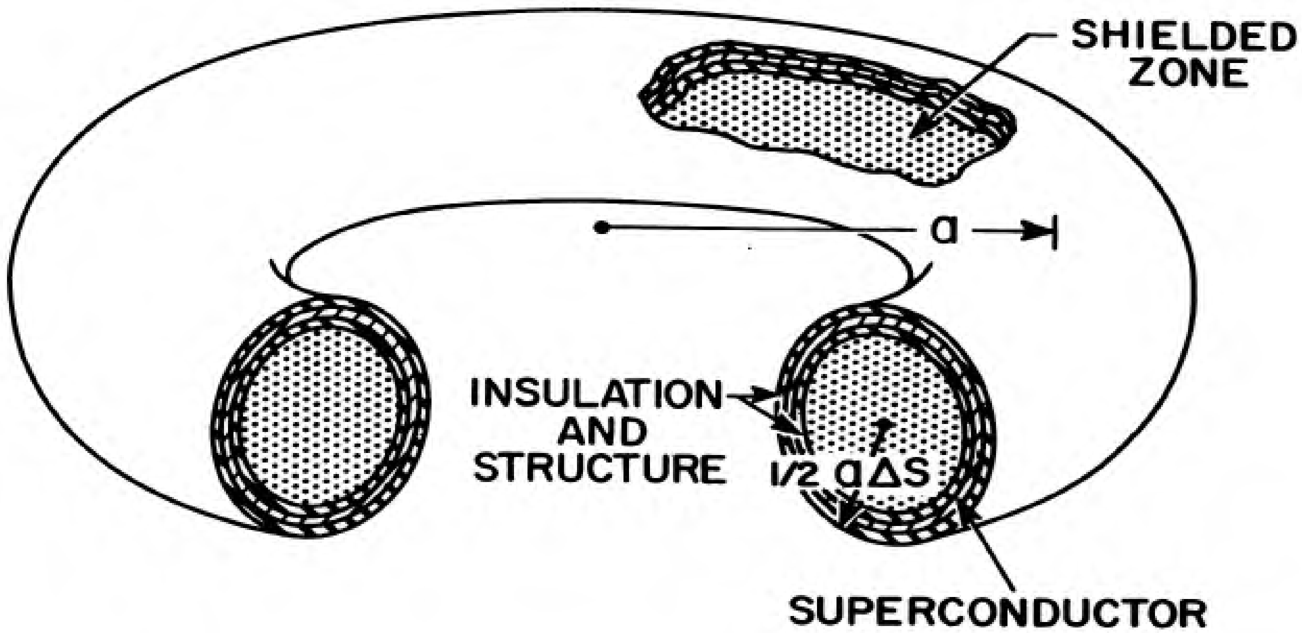

Fig. 5 This magnetic shield was discussed in Ref. 1. The shielded volume is tubular in shape, and the magnetic field is confined to the exterior of the shielded volume.

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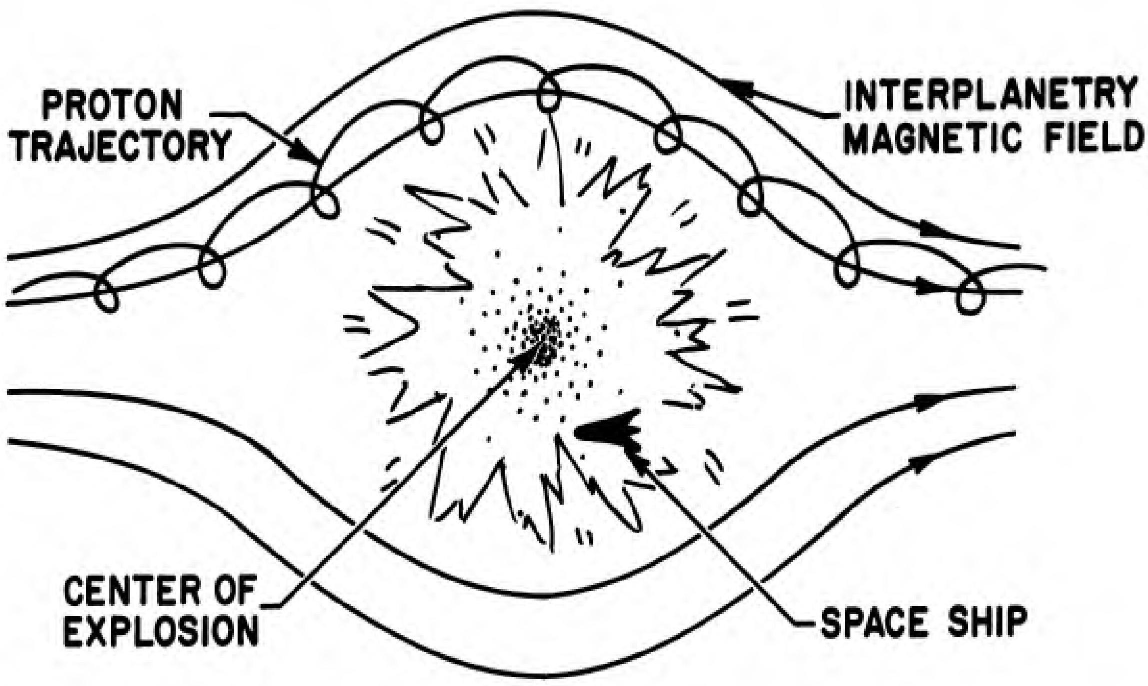

Fig. 6 This figure illustrates the explosive method of shielding discussed in the text. The size of the hole made in the magnetic field should be greater than the Larmor radius of the incident protons.

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November 1962. 14 p. incl. illus. (Avco-Everett AMP 94)
(Contract Nonr-2524(00))

Unclassified report

A review is given of the reasons for the interest in active shielding and the types of missions for which an active shield would be particularly desirable are discussed. Recent work on active shielding is reviewed. Electrostatic shielding is then discussed. In general, the maintenance of an electrostatic field for shielding purposes will require the expenditure of power owing to the presence of a neutral highly conducting plasma. Estimates of the power required are extremely high, and electrostatic shielding appears unattractive. Magnetic shielding is discussed next. The virial theorem on the weights of magnetic field coils in space is explained, and it is shown how this theorem can be used to make a direct comparison between the use of a material as an element in a

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